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Squeezing of Atomic Variables in the One-Photon and Two-Photon Jaynes-Cummings Model

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Squeezing of atomic variables in the one-photon and two-photon Jaynes-Cummings model

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Abstract

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I. Introduction

It is by now well known that squeezed light has potential applications in low-noise communications and high-precision measurments involving light.[1,2] The Jaynes-Cummings (JC) model[3,4] is one of the possible nonlinear optical models capable of creating squeezed states.[5] A number of calculations of field squeezing have been made in recent years. In the standard JC model, the maximum field squeezing was found to be 20%,[5] but in a recent paper it was argued that this squeezing could be 100%.[6] When the initial coherent state of the field is replaced by the vacuum state, the maximum squeezing is increased to 25%.[7] More squeezing is found in many other cases of the generalized JC model. The maximum squeezing is 42% for two-level two-photon,[8] 57% for two-level three-photon,[9] 31% for three-level one-mode,[10] 36% for four-level one-mode,[11] and 52% for ten-level one-mode[12] cases. However, little attention has been paid to the squeezing of the atomic variables. The squeezing of the atomic dipole operators for a two-level atom driven by a classical field[13] has been investigated. A general relation has been established between the coherent states of the SU(2) and SU(1,1) Lie algebra and possible reduction of fluctuations in angular momentum.[14] For the special case of a vacuum initial field mode, the relation between the atomic variable squeezing and the field squeezing has been examined.[15] Only recently, a quantum mechanical study devoted to the squeezing of the atomic dipole moment has been carried out,[16] where it is found that a maximum squeezing of 60% can be reached.

In this note we calculate the squeezing of the atomic dipole moment in the one-photon and two-photon JC model with different initial conditions. It is found that the atomic variables generally possess stronger squeezing than the field under the same conditions. In particular circumstances, a nearly pure squeezing state can be achieved. In the standard JC model, a one-mode cavity field with frequency Ω couples to a two-level atom through the well-known Hamiltonian in the rotating-wave approximation,

$$H = \frac{1}{2}\hbar\omega\sigma_3 + \hbar\Omega a^\dagger a + \hbar\lambda(a^\dagger\sigma^- + a\sigma^+) \quad , \tag{1}$$

where $a^\dagger(a)$ and Ω are the creation (annihilation) operator and frequency of the cavity field, respectively, and λ is the coupling constant. The two-level atom with transition frequency ω is described by the Pauli raising and lowering operators $\sigma^\pm$ and the inversion operator $\sigma_3 = \sigma^+\sigma^- - \sigma^-\sigma^+$. The dispersive and absorptive components of the slowly-varying atomic dipole[17] can be written as

$$\sigma_1 = \frac{1}{2}(\sigma^+e^{-i\omega t} + \sigma^-e^{i\omega t}) \tag{2}$$

and

$$\sigma_2 = \frac{1}{2i}(\sigma^+e^{-i\omega t} - \sigma^-e^{i\omega t}) \quad , \tag{3}$$

respectively. They obey the commutation relation

$$[\sigma_1,\sigma_2] = \frac{i}{2}\sigma_3 \tag{4}$$

and the corresponding uncertainty relation

$$(\Delta\sigma_1)^2(\Delta\sigma_2)^2 \geq \frac{1}{16}\langle\sigma_3\rangle^2 \quad . \tag{5}$$

The atomic state is said to be squeezed when σ_1 or σ_2 satisfies the relation

$$(\Delta\sigma_i)^2 < \frac{1}{4}|<\sigma_3>| \quad , \qquad i = 1,2 \quad . \tag{6}$$

Since

$$(\Delta\sigma_1)^2 = \frac{1}{4} - (\mathrm{Re}<\sigma^->e^{i\omega t})^2 \tag{7a}$$

$$(\Delta\sigma_2)^2 = \frac{1}{4} - (\mathrm{Im}<\sigma^->e^{i\omega t})^2 \quad , \tag{7b}$$

the condition described by Eq. (6) can be rewritten as

$$S_1 = \frac{1 - 4(\mathrm{re}<\sigma^->e^{i\omega t})^2}{|<\sigma_3>|} < 1 \tag{8a}$$

or

$$S_2 = \frac{1 - 4(\mathrm{Im}<\sigma^->e^{i\omega t})^2}{|<\sigma_3>|} < 1 \tag{8b}$$

for squeezing in the dispersive or absorptive component of the dipole. In what follows we shall investigate this squeezing effect by using different initial conditions for the atom and the cavity field.

II. Squeezing in the JC model

We denote by $|+>$ and $|->$ the excited and ground states of the atom and by $|n>$ the Fock states of the field. First we consider the initial condition that the atom is in the excited state and the field in a two-photon coherent state or squeezed state,[1,2,18]

$$|\alpha,r\rangle = \sum_n F(n)|n\rangle \tag{9}$$

$$F(n) = (n!\cosh r)^{\frac{1}{2}}\left(\frac{\beta}{2\cosh r}\right)^n Y^{-n} H_n(Y) \exp\left[-\frac{\beta^2}{2}(1 - \tanh r)\right] , \tag{10}$$

where $\beta = \alpha e^r$ and $Y = \beta(2\cosh r \sinh r)^{-\frac{1}{2}}$, and we have chosen the squeezing parameter r to be real.[19] The initial mean photon number is given by $\bar{n} = |\alpha|^2 + \sinh^2 r$, so that the initial state vector for the atomic-field system can be written as

$$|\psi(0)\rangle = \sum_n F(n)\ |+,n\rangle \quad . \tag{11}$$

At a time $t > 0$, the state vector in the interaction picture is found from the JC model Hamiltonian (1) to be

$$|\psi(t)\rangle = \sum_n F(n)[A(n,t)|+,n\rangle + B(n+1,t)\ |-,n+1\rangle] \quad , \tag{12}$$

where

$$A(n,t) = e^{-i\Delta t/2}\ (\cos\mu t + i\frac{\Delta}{2}\sin\mu t/\mu) \tag{13}$$

$$B(n+1,t) = -i\frac{V}{\mu}\ e^{-i\Delta t/2}\ \sin\mu t \quad , \tag{14}$$

with $V = \lambda\sqrt{n+1}$, $\mu^2 = V^2 + \Delta^2/4$ and $\Delta = \Omega - \omega$. From Eqs. (12)-(14), we obtain the expectation values of the atomic operators:

$$\langle\sigma^-\rangle e^{i\omega t} = \langle\psi(t)|\sigma^- e^{i\omega t}|\psi(t)\rangle$$

$$= \sum_{n=0}^{\infty} F^*(n)F(n+1)B^*(n+1)A(n+1) \tag{15}$$

$$\langle\sigma_3\rangle = \sum_{n=0}^{\infty} |F(n)|^2[|A(n)|^2 - |B(n+1)|^2] \quad . \tag{16}$$

The time evolutions of S_1 and S_2 are calculated for the case of off-resonant excitation with medium strength. The units employed throughout this paper are λ for energy and λ^{-1} for time. The results are presented in Fig. 1. It is observed that σ_1 and σ_2 are squeezed alternatively. Roughly speaking, the squeezing parameters S_1 and S_2 oscillate at about the same frequency but out of phase. A more careful analysis reveals that both are composed of two oscillations with different frequencies. The maximum squeezing in this case is approximately 25% for both S_1 and S_2.

For the case of on-resonance excitation, $\langle\sigma_1\rangle$ is zero but its fluctuation is still nonvanishing because of quantum mechanical effects. Figure 2 shows the time evolution of S_2 for the on-resonance excitation by a squeezed and a coherent light field. A comparison of (a) and (b) in Fig. 2 shows that squeezing occurs only for a short time after the interaction is turned on when the initial field is in a coherent state. The maximum squeezings in these cases are, however, about the same, namely, 65% and 68% for the coherent and squeezed excitations, respectively. The role played by the detuning can be clearly seen by comparing Figs. 1(b) and 2(a). Evidently, a larger detuning implies weaker coupling between the atom and the field and hence less squeezing. Although the results shown are obtained for the same $\bar{n}$, we have found from our numerical study that in general a larger exciting strength or larger $\bar{n}$ results in stronger squeezing effects.

Next we consider a vacuum initial field in the JC model. The atom is injected into the field in a coherent superposition of excited and ground states,[7]

$$|\psi(0)\rangle = e^{i\phi}\cos\theta|-,0\rangle + \sin\theta|+,0\rangle \quad . \tag{17}$$

From the Hamiltonian (1) and Eq. (17), the state vector at time t > 0 can be written as

$$|\psi(t)\rangle = C_0^-|-,0\rangle + C_1^-|-,1\rangle + C_0^+|+,0\rangle \quad , \tag{18}$$

where

$$C_1^-(t) = -i\sin\theta\sin\lambda t \tag{19}$$

$$C_0^+(t) = \sin\theta\cos\lambda t \tag{20}$$

$$C_0^-(r) = e^{i\phi}\cos\theta \quad . \tag{21}$$

Using the same procedure as outlined above, we can write

$$\langle\sigma^-\rangle e^{i\omega t} = \langle\psi(t)|\sigma^- e^{i\omega t}|\psi(t)\rangle = C_o^{-*}C_0^+ = \frac{1}{2}\, e^{-i\phi}\sin 2\theta\cos\lambda t \tag{22}$$

and

$$<\sigma_3> = 1 - 2\sin^2\theta\cos^2\lambda t \quad . \tag{23}$$

Inserting Eqs. (22) and (23) into (8), we find the squeezing parameters as

$$S_1 = (1 - \sin^2 2\theta\cos^2\phi\cos^2\lambda t)/|1 - 2\sin^2\theta\cos^2\lambda t| \quad , \tag{24}$$

$$S_2 = (1 - \sin^2 2\theta\sin^2\phi\cos^2\lambda t)/|1 - 2\sin^2\theta\cos^2\lambda t| \quad . \tag{25}$$

From these two equations one can see that when the atom starts in a purely excited state, i.e., $\theta = \frac{\pi}{2}$, there is no squeezing effect. It is apparent that maximum squeezing occurs when $\lambda t = k\pi$ $(k = 0,1,2,\ldots)$ and $\phi = k\pi$ (for σ_1) or $(k+\frac{1}{2})\pi$ (for σ_2). We have, under these conditions,

$$S_i = (1 - \sin^2 2\theta)/|1 - 2\sin^2\theta| = |\cos 2\theta| \quad , \tag{26}$$

where $\theta = \frac{1}{2}(k+\frac{1}{2})\pi$. Equation (20) yields

$$S_i = 0 \quad . \tag{27}$$

This means that the maximum squeezing of 100% is possible.

III. Squeezing in two-photon processes

A simple model for atom-radiation interaction that can be solved analytically has recently been proposed.[7] It involves two-photon Raman coupling between two atomic states $|+\rangle$ and $|-\rangle$ degenerate in energy. The Hamiltonian for this model is therefore

$$H = \hbar\Omega a^{\dagger}a + \hbar\lambda a^{\dagger}a(\sigma^{-} + \sigma^{+}) \quad , \tag{28}$$

where we have set the atomic transition frequency to be zero because of the degeneracy. It has been shown that the system has perfect revival.[7] Here we shall study the squeezing of the atomic dipole operator in this model.

We assume that the atom starts in the initial state $|+\rangle$ and the field is in a coherent state $|\alpha\rangle$,

$$|\alpha\rangle = \sum_{n} G(n)|n\rangle \tag{29}$$

$$G(n) = \frac{\alpha^{n}}{\sqrt{n!}} e^{-\bar{n}/2} \quad , \tag{30}$$

where $\bar{n} = |\alpha|^2$ is the initial mean photon number of the field. The initial state vector then takes the form

$$|\psi(0)\rangle = \sum_{n} G(n)|+,n\rangle \quad . \tag{31}$$

At any time $t > 0$, the state vector can be written as

$$|\psi(t)\rangle = \sum_{n=0}^{\infty} G(n)[D^{+}(n)|+,n\rangle + D^{-}(n)|-,n\rangle] \quad , \tag{32}$$

where

$$D^{+}(n,t) = \cos(\lambda nt) \tag{33a}$$

$$D^{-}(n,t) = -\, i\sin(\lambda nt) \quad . \tag{33b}$$

From Eqs. (32) and (33), one can easily find the mean value of the atomic dipole moment as

$$\langle\sigma^{-}\rangle = \frac{i}{2}\sum_{n=0}^{\infty} e^{-\bar{n}}\,\frac{\bar{n}^{n}}{n!}\sin(2\lambda nt) = \frac{i}{2}\exp[-\,2\bar{n}\,\sin^{2}(\lambda t)]\sin[\bar{n}(\sin 2\lambda t)] \tag{34}$$

and the inversion

$$\langle\sigma_{3}\rangle = \exp(-\,2\bar{n}\,\sin^{2}\lambda t)\cos(\bar{n}\,\sin 2\lambda t) \quad . \tag{35}$$

It is clear that the mean value of the dispersive component for the atomic dipole fluctuates around zero. Hence there is no squeezing in this component. As for the squeezing in the other component σ_2, we find from Eqs. (8), (34) and (35)

$$S_{2} = \frac{1 - \exp(-4\bar{n}\,\sin^{2}\lambda t)\sin^{2}(\bar{n}\,\sin 2\lambda t)}{\exp(-2\bar{n}\,\sin^{2}\lambda t)\,|\cos(\bar{n}\,\sin 2\lambda t)|} \quad . \tag{36}$$

To find the maximum magnitude of squeezing, we may consider the case where $\bar{n} >> 1$ but $\bar{n}(\lambda t)^2 << 1$. Thus we have

$$S_2 \approx \frac{1 - [1 - 4\bar{n}(\lambda t)^2]\sin^2(2\bar{n}\lambda t)}{|\cos(2\bar{n}\lambda t)|}$$

$$= \frac{1 - (1 - \bar{n}^{-1}x)\sin^2 x}{|\cos x|} \quad , \tag{37}$$

where $x = 2\bar{n}\lambda t$. When x is in the vicinity of $\frac{\pi}{2}$, i.e., $x = \frac{\pi}{2} - \epsilon$ with $\frac{1}{\bar{n}} << \epsilon << 1$, we may expand sinx and cosx in a Taylor series around $\frac{\pi}{2}$ to the second term. Hence, for $\lambda t \approx \frac{\pi}{4}\bar{n}^{-1}$ we have

$$S_2 \approx \frac{\pi^2}{4}(\bar{n}\epsilon)^{-1} \quad . \tag{38}$$

Equation (38) implies that for strong excitation, S_2 is very small and the maximum magnitude of squeezing is nearly 100%.

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Figure Captions

1. Time evolution of the squeezing parameters (a) S_1 and (b) S_2 calculated for the case of off-resonance excitation. The parameters used are $\bar{n}$ = 100, r = 1 and Δ = 50.

2. Time evolution of S_2 for the case of on-resonance excitation by a (a) squeezed (r = 1) and (b) coherent (r = 0) field with $\bar{n}$ = 100.

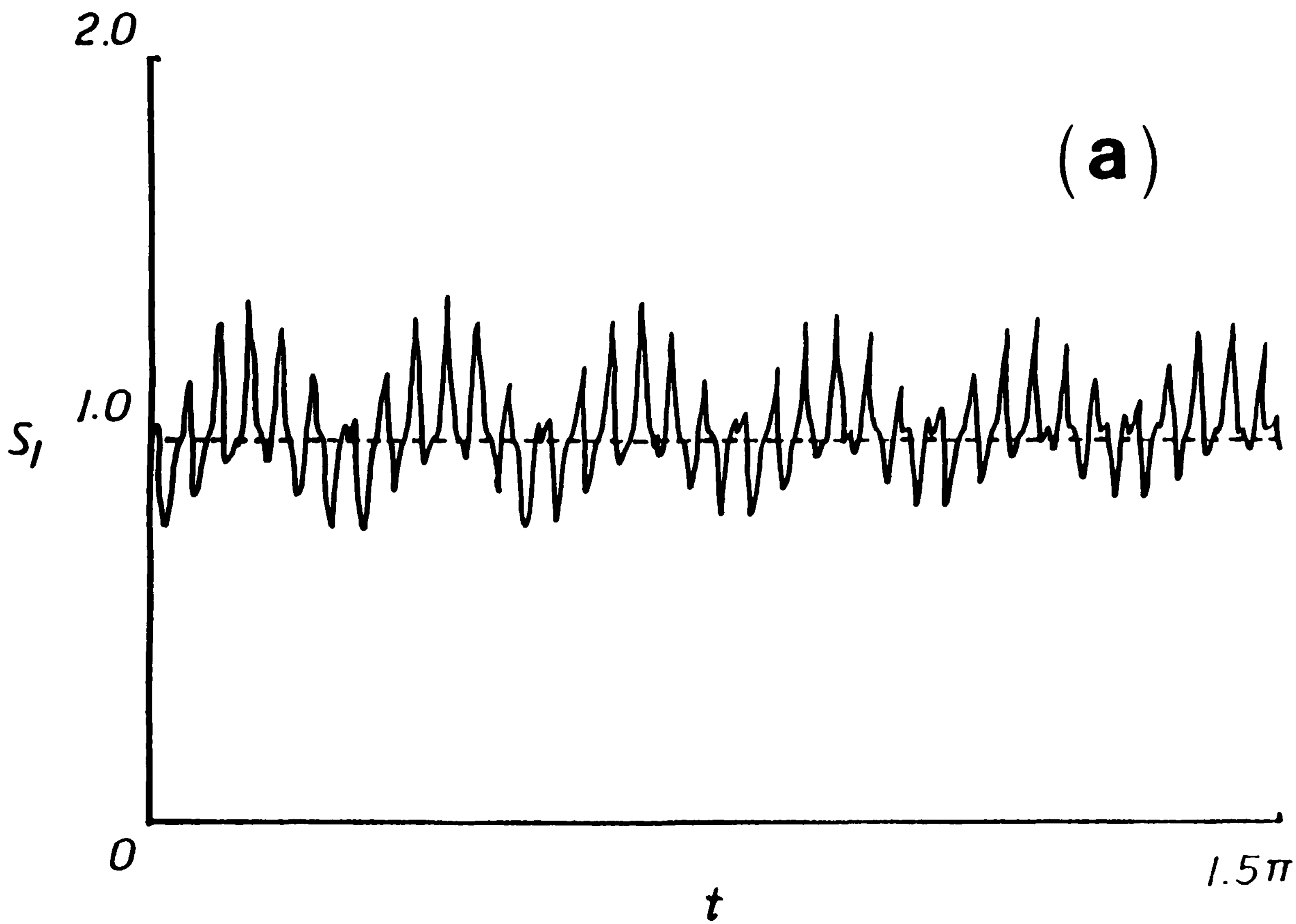

Fig. 1(a)

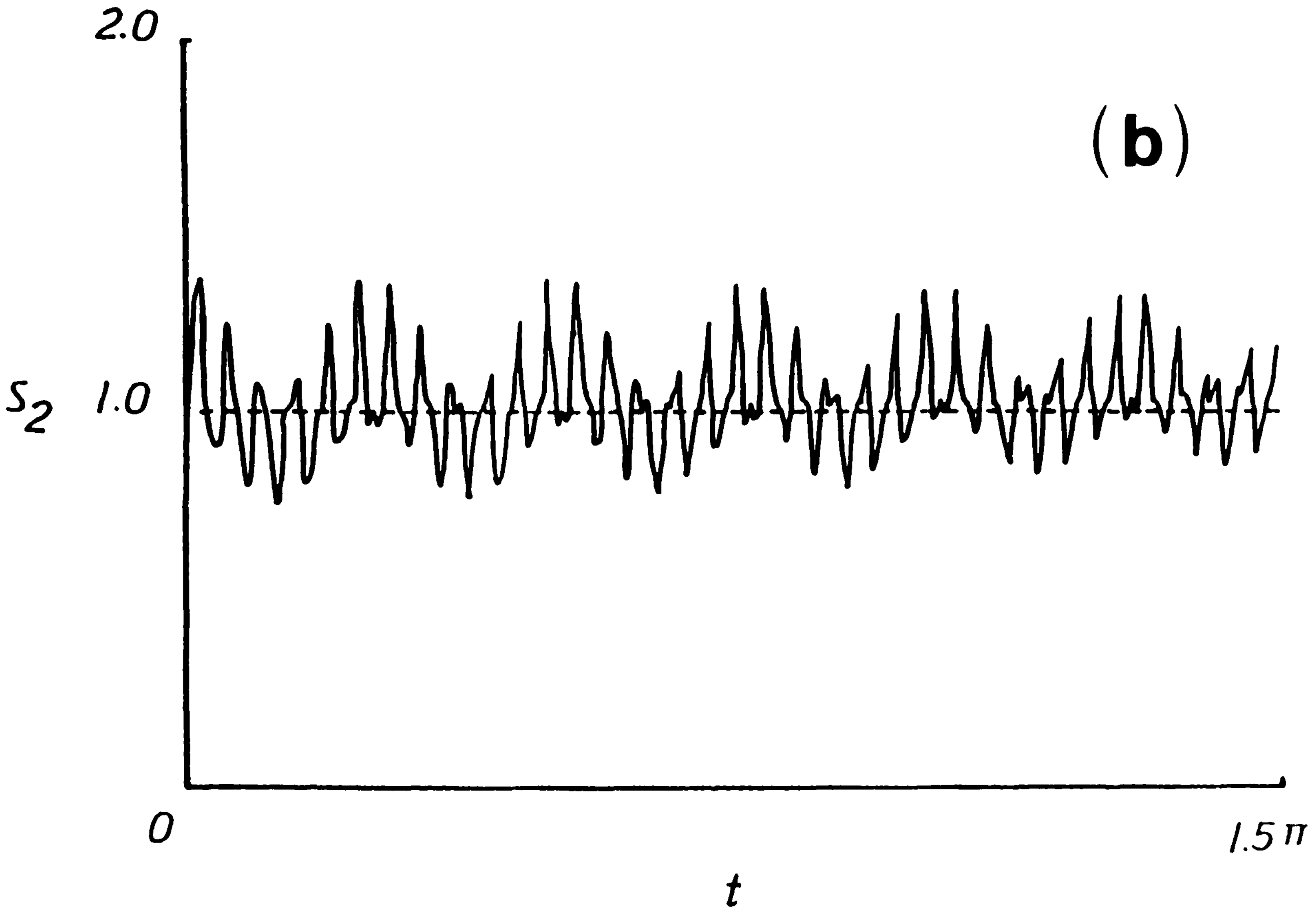

Fig 1(b)

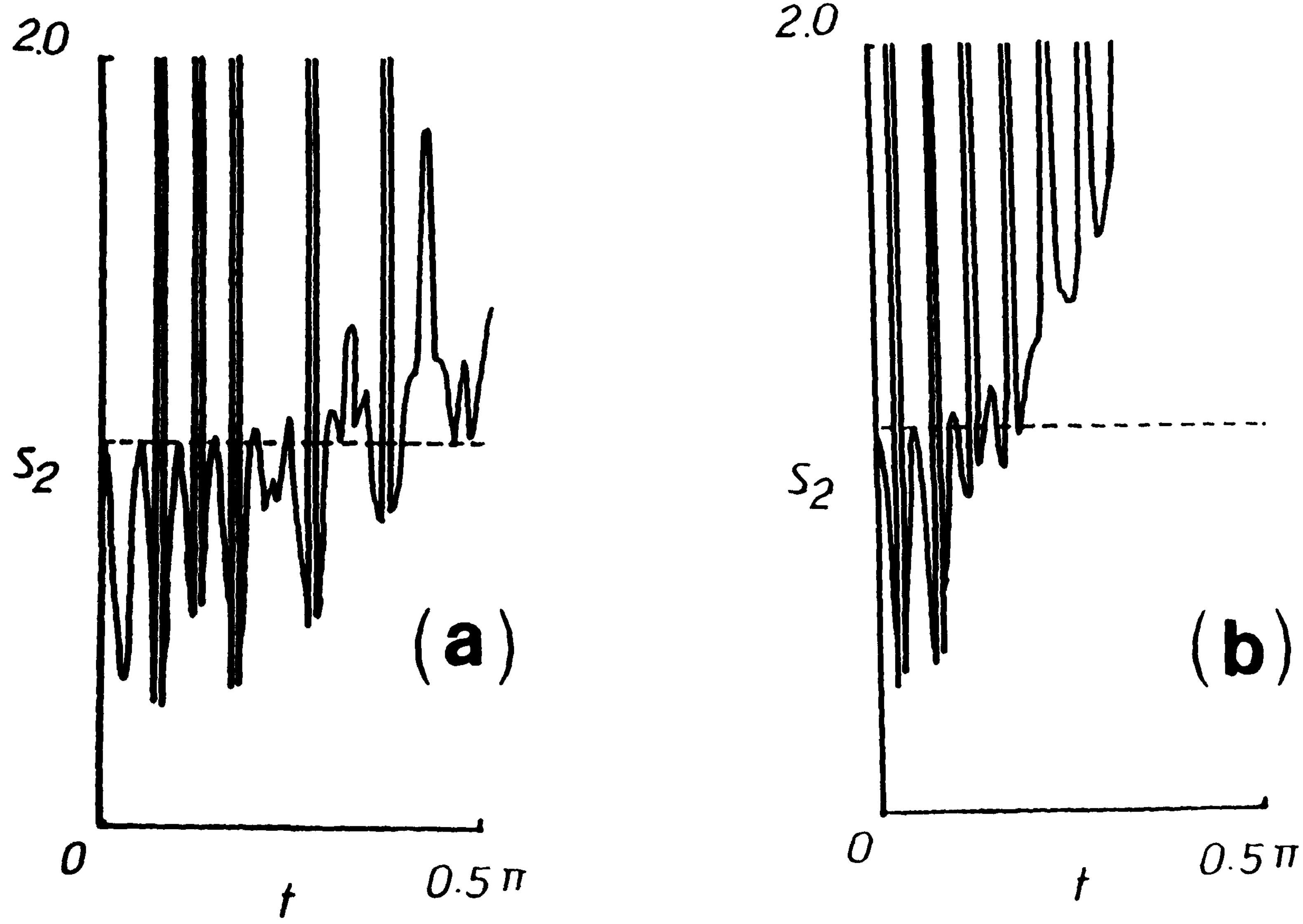

Fig. 2

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